

What is a Capacitor?

- ✓ **Capacitors in General**
- ✓ **Ceramic Capacitors**
- ✓ **Tantalum Capacitors**

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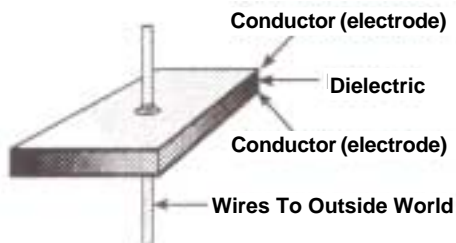
F-2856E 1-96
Reprinted 6-01

PART I

FUNDAMENTALS FOR ALL CAPACITORS

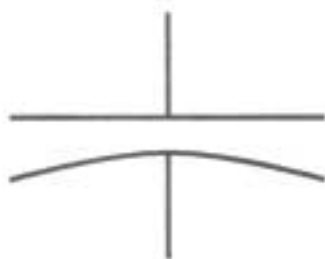
This bulletin describes the basic characteristics of KEMET capacitors. Before examining all the details relating to KEMET products, here are some of the basics of all capacitors and then of the major types sold under the KEMET brands: solid tantalum and monolithic ceramic.

For all practical purposes, consider only the parallel-plate capacitor: two conductors or electrodes separated by a dielectric material of uniform thickness. The conductors can be any material which will conduct electricity easily. The dielectric material must be a poor conductor – an insulator.



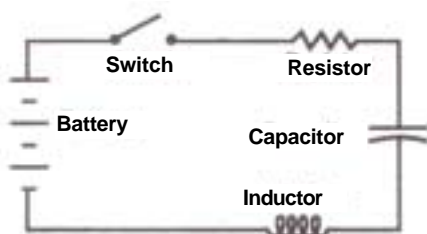
The Parallel - Plate Capacitor

The symbol for a capacitor used in schematic diagrams of electronic circuits looks very much like a parallel-plate model.



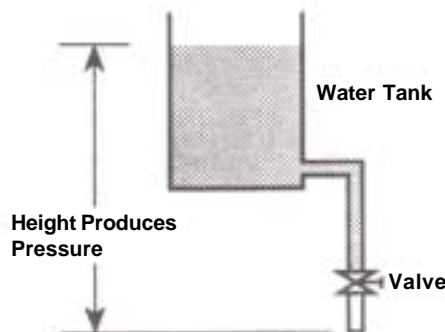
Capacitor Symbol

Here is a sample circuit which contains all the components normally called “passive,” plus a battery. The battery is an “active” component because it can add energy to the circuit. Passive components may store energy momentarily, but cannot add energy on a continuous basis. The three main passive devices are resistors, capacitors, and inductors.



Passive Components in Series with a Battery

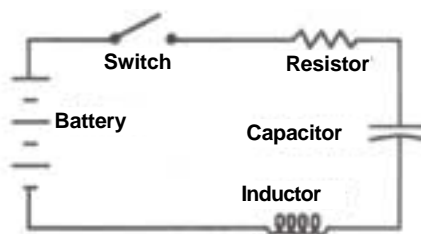
A favorite analogy compares the flow of electric current with the flow of water out of a tank. A capacitor stores energy when it is charged. The water tank would be the capacitor and it would be charged by a pump (a battery) which fills it up. The amount of charge in the capacitor would be analogous to the amount of water in the tank. The height of the water above some reference point would be the voltage to which the battery had pumped up the capacitor, and the area of the tank would be capacitance. A tall, skinny tank might contain the same amount of water as a shallow, flat tank, but the tall, skinny tank would hold it at a higher pressure. There are also tall, skinny capacitors (high voltage, low capacitance) and shallow, flat capacitors (low voltage, high capacitance).



Water Tank Analogy

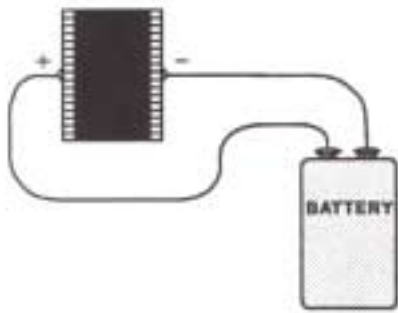
There is also a pipe coming out of the tank and a valve. If the valve is open, water runs out. The valve is both a switch and a resistor. If the valve is opened only partially, it causes enough friction so that water runs slowly from the tank. It behaves like a variable resistor. When resistance is high, the water runs slowly, but if resistance is made small, the water can run more freely. Once the water is running, it can be stopped by closing the valve. The water in the pipe, already in motion, must stop. If the valve is closed very quickly, then the water must stop flowing very quickly. Water “hammers” in some plumbing systems which causes a distant “clunk” when a valve is closed quickly. The energy in the moving water suddenly has no place to go, so it bangs a pipe against its support somewhere.

The moving water has acted like the inductor acts in the electronic circuit. The battery is the pump, the capacitor is the tank, the resistor and the switch are the valve, and the inductor is the moving water in the pipe.



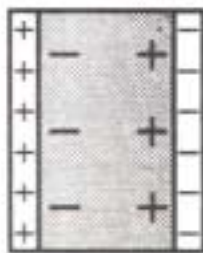
Passive Components in Series with a Battery

What happens inside a capacitor? When charged by a battery, one electrode of the capacitor will become positively charged and the other one will be correspondingly negatively charged.



Charged Capacitor

When the diagram of the capacitor is magnified, it can be seen that the presence of electrical charges on the electrodes induces charges in the dielectric. These induced charges determine something called permittivity. Each different dielectric material has its own value of permittivity. A more practical and better known measurement tool is called “K,” or dielectric constant. “K” is the *ratio* of the permittivity of the dielectric in use to the permittivity of free space – a vacuum. Therefore, all the capacitance values are related to the permittivity of vacuum.

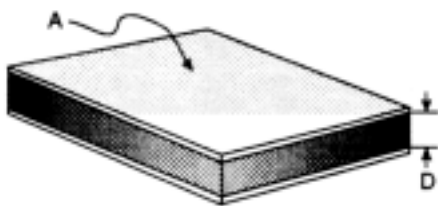


Charges inside the Capacitor

In a vacuum, $K = 1$, while “K” in every material has some value greater than 1. The higher the “K,” the more capacitance can be realized, with all other things being equal.

The expression of capacitance is seen here, and note the presence of the constant, 8.85×10^{-12} (permittivity of vacuum).

$$C = (8.85 \times 10^{-12}) K \frac{A}{D}$$



The Capacitor Equation

The only trick involved in using this equation is to keep the units consistent. Capacitance is in farads, the area “A” is in square meters and the distance between electrodes “D” is in meters. “K” is a ratio and a pure number without dimensions.

Sometimes different constants are used in the equation. This comes about when units other than farads and meters are used. Microfarads and inches might be used, for example.

To get an idea of what a farad is, calculate the area which would be necessary in a capacitor built to have one farad, to operate in a vacuum, and to have a spacing between electrodes of one millimeter. First, turn the equation around to solve for the area and then plug in the values known. This calculates to 113 million square meters, which would be a field about 6.5 miles on a side. It’s not hard to see why one farad capacitors aren’t made very often and when they are, they are never made with a vacuum dielectric and a one millimeter spacing. Vacuum capacitors are made, but the market is pretty well limited to laboratory standards. All commercial capacitors use some different dielectric material with a higher value of K.

$$C = (8.85 \times 10^{-12}) K \frac{A}{D} \text{ or } A = \frac{CD}{(8.85 \times 10^{-12}) K}$$

$$\text{Given: } K = 1 \\ C = 1 \text{ farad}$$

$$D = 1 \text{ millimeter (or } 0.001 \text{ meters)}$$

$$A = \frac{1 \times 0.001}{(8.85 \times 10^{-12}) \times 1} = 113,000,000 \text{ sq. meters}$$

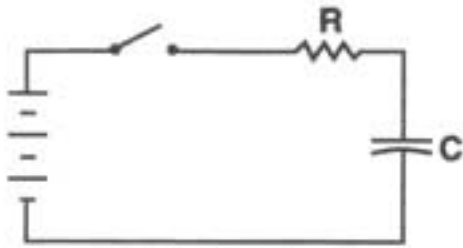
A One-Farad Vacuum Capacitor

Materials used today are in the table below. There is a tendency toward the higher values of K. (With a K of 10, there would be a reduction of one farad capacitor area to a mere 11.3 million square meters!) The wide range in values for barium titanate, which is the basis for most ceramic capacitors, is an unfortunate fact of nature which will be discussed more completely later on. Why make commercial capacitors with any of the materials having low values of K? The answer generally less with other capacitor characteristics such as stability with respect to temperature, voltage ratings, etc. These will all be explored through investigation of other dielectric systems later on.

Material	K at 25°C
Vacuum	1
Glass	5 to 10
Mica	3 to 6
Plastics, general	2 to 4
Aluminum Oxide, Al_2O_3	10
Tantalum Oxide TA_2O_5	26
Barium Titanate, $BA TiO_3$	1,000 to 30,000

Values of Dielectric Constant K

What is the behavior of capacitors when they are connected in circuits? Probable the simplest is the RC timing circuit. It is called RC because the combination of resistance (R) and capacitance (C) determines its operation.

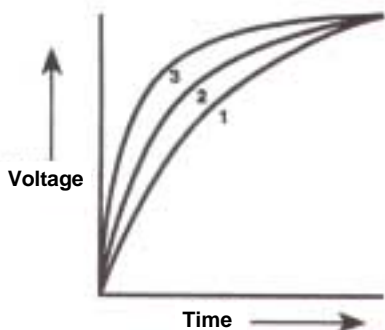


The R C Timing Circuit

When the switch is closed, current from the battery flows through the circuit, charging the capacitor. When the capacitor is completely charged, it is like a closed tank which is completely filled up, and no further current flows. At that time, the voltage across the capacitor would be equal to the supply voltage of the battery. Voltage across the capacitor advances from zero (fully discharge) to the supply voltage along some predetermined path with respect to time. If the resistor is small, current flows easily and the capacitor is charged more quickly. If there is a very large resistor, the charging process follows a different path and will take longer to complete.

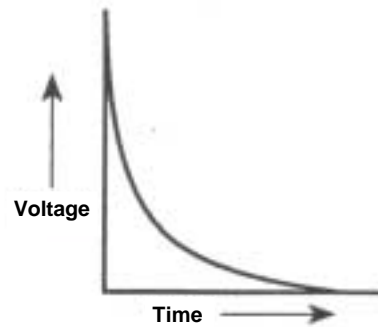
The behavior of voltage versus time is also influenced by the size of the capacitor. If the capacitor's capacitance is very large, it will require more total energy to fill (the tank is large in diameter), and current flowing through the resistor will require a longer time to charge it.

Below are three charging curves, each approaching the same end point but along different paths. (By adjusting the value of resistance in R and the capacitance in C, curves 1, 2, 3, and many others can be formed.) What good is it? To be able to leave the lights on in a car and have them go off automatically after a predetermined amount of time, the voltage across the capacitor would operate a switch when it reaches some predetermined value. If other considerations in this circuit required that the switch be operated on a decreasing voltage rather than an increasing voltage, the voltage which appears across the resistor could be used.



Voltage across Capacitor In R C Circuit

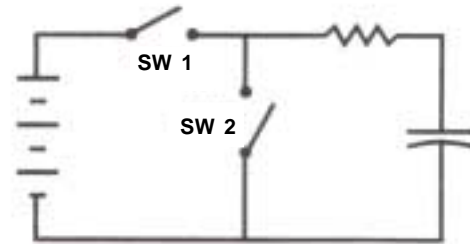
The instant the switch is closed, all the voltage of the battery would appear across the resistor and none across the capacitor. The voltage across the resistor would decrease with time just as the voltage across the capacitor increases with time.



Voltage across Capacitor in R C Circuit

DIRECT CURRENT (DC)

The timing circuit is a good example of a DC application. Note that the capacitor blocks flow of DC once it is charged. Current would flow once more if connected to another switch to discharge the capacitor. If switch No. 1 was opened and switch No. 2 was closed, the stored energy in the capacitor would flow as current through the resistor until the voltage across the capacitor reached zero. The capacitor can thus be compared to a storage battery, although the principles of operation are entirely different.



Discharge via Switch No. 2

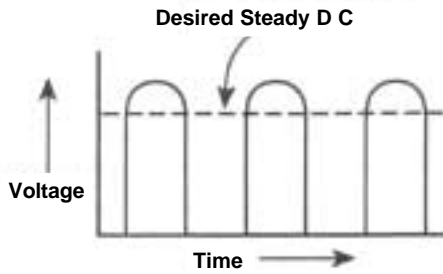
The storage capability of the capacitor is used to good effect in filters. A DC power supply offers a good example. Basic DC power supplies provide an output (that is, the voltage across a load, shown here as a resistor) which is fluctuating.



Measuring Voltage from a Power Supply

The following figure shows a situation where the voltage drops completely to zero. The goal is a straight line across this graph representing a steady DC voltage.

Adding a capacitor to the circuit will smooth these fluctuations and approach the desired straight line. Starting with the voltage at zero and the capacitor discharged, turn on the supply. As the voltage begins to rise, some current will flow to charge the capacitor while the rest passes through the resistor. Some time before the capacitor is completely charged, the voltage from the supply will begin to decline: as soon as the supply voltage



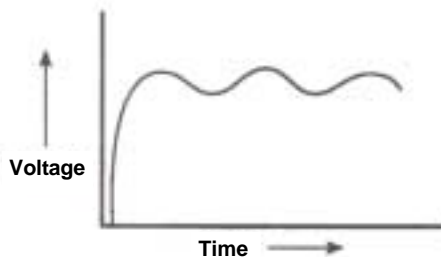
**Fluctuating D C Voltage
from a Power Supply**

is below the capacitor voltage, the capacitor will begin to discharge, and the current will flow from the capacitor, maintaining the voltage across the resistor. If the value of capacitance is chosen correctly, the capacitor cannot be totally discharged during the time available, and the capacitor will be charged once more as the supply voltage exceeds the capacitor voltage.



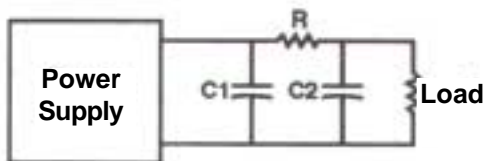
Filter Capacitor Added

The result of a simple filter of this sort will not produce the desired steady DC voltage (a perfectly straight line on the graph), but it will produce a wave form something like that seen below.



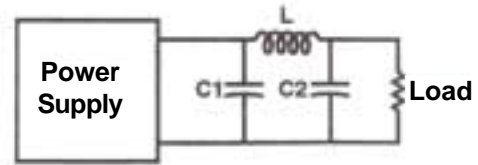
Filtered DC

The condition can be improved further by adding a series resistor and another capacitor.



Improved Filter

An even better result can be obtained if an inductor is used instead of the series resistor. (Remember the water that wanted to keep running through the pipe?)

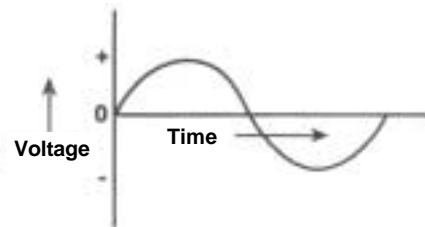


Even Better Filtering

ALTERNATING CURRENT (AC)

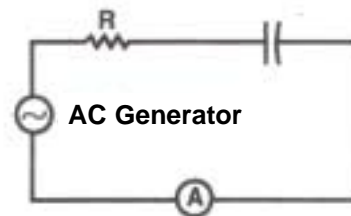
With alternating current, the voltage goes from zero to some maximum value, back down to zero, and then in the negative direction before returning to zero once more. Alternating current frequently does look exactly like that shown, which is a sine wave. If it doesn't look like this, engineers find some way to transform their calculations so that they can then use all the mathematics which lie behind the sine wave.

What happens when a capacitor is subjected to alternating current? To the capacitor, it looks just like DC which is flowing in and flowing out again. The capacitor is alternately being charged, discharged, and then recharged in the opposite direction before being discharged again. One fact important to note is that the capacitor can never block the flow of AC but instead permits a steady flow of current. This throws the timing circuit out the window, but it opens up a lot of new possibilities.



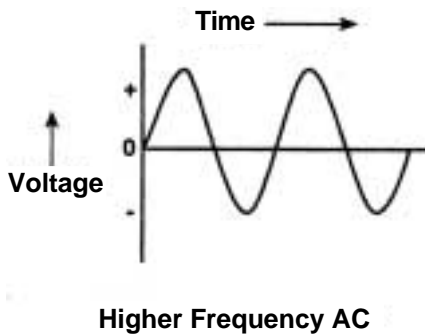
Alternating Current-The Sine Wave

Consider how much current flows through the circuit. If the generator's sine-wave and the resistance, "R," don't change, current flow depends upon only two things. The first is the size of the capacitor, its capacitance. With a large capacitor, there will be insufficient time for it to be charged more than a small amount before the current direction reverses and it is discharged again. Current flows very easily when the capacitor is near its discharged state, as noted with the timing circuit. If the capacitor is small, it might approach the completely charged state before the current reverses direction and discharges it. The smaller capacitor would thus offer much more hindrance to passage of the current.



Meter to Measure Current

The second factor affecting current flow is the frequency of the alternating current. If, instead of the previous wave form, there is one in which current reversal takes place in half the time (double the frequency), the amount of energy which flows into the capacitor before current reversal will be much less. In effect, the capacitor will stay closer to its discharged state than when the frequency of the wave form was lower. Consequently, the hindrance to current flow that the capacitor offers will be less.



The capacitor, in an AC circuit, is acting something like a resistor in a DC circuit. The additional dimension of frequency has to be a consideration.

The two effects of frequency and capacitor size (capacitance) are combined in an expression known as capacitive reactance and symbolized as X_C . Note that X_C is expressed in ohms, which is the unit of resistance. Reactance acts something like resistance, and the same unit is used because the two will be combined later. The frequency is expressed as the number of alternations (complete sine waves) which occur in one second, and it used to be abbreviated "cps" for "cycles per second," but is now expressed in hertz. Note that capacitive reactance is inversely proportional to both frequency and capacitance. This fits exactly with the earlier explanation concerning the ease of charge and discharge of a capacitor when it was operating near its discharged state.

$$X_C = \frac{1}{2\pi fC}$$

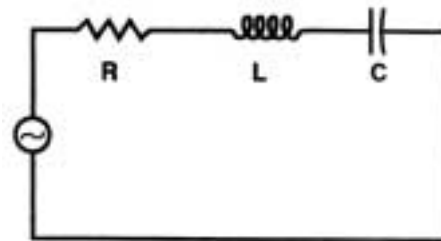
X_C = capacitance, reactance, ohm
 π = 3.14
 f = frequency, hertz
 C = capacitance, farad

There is a comparable expression for inductance which yields inductive reactance. The unit of inductance is the Henry. It follows that inductance in an AC circuit impeded the flow of the current just as a capacitor does. The difference is that X_L is directly proportional to both frequency and inductance. The larger the inductor and the higher the frequency, the greater is the reactance to current flow: just the opposite of the behavior of a capacitor's X_C .

$$X_L = 2\pi fL$$

X_L = inductive reactance, ohm
 π = 3.14
 f = frequency, hertz
 L = inductance, henry

Capacitors include both resistance and inductance, because it is not possible to make practical devices completely lacking in these factors. Below is a series circuit with all three: resistance, inductance and capacitance, and all capacitors actually look something like this. If the capacitor is a good one, the amount of resistance and inductance is very small compared to the amount of capacitance. In an AC circuit, all three components act to decrease the flow of current. The sum effect of all three is termed "impedance." Impedance is expressed in ohms just like resistance, and it would be nice to simply add X_L , X_C , and R to get impedance, Z .

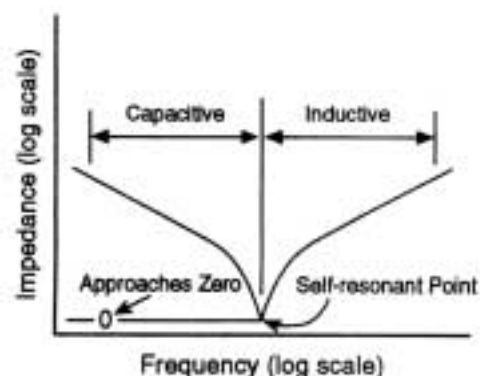


Passive Elements in a Series AC Circuit

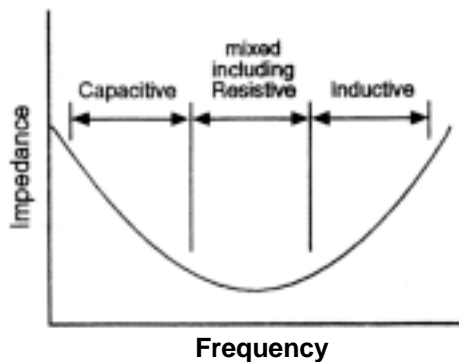
Unfortunately, it isn't quite that simple because of other factors which are beyond this discussion. X_L and X_C can be added or subtracted directly, but they must be combined with R by the squaring and square root process indicated here.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

In KEMET capacitor catalogs, there are graphs of impedance versus frequency. Impedance becomes a useful consideration at higher frequencies because the capacitive effect disappears at some frequency dependent on capacitor design. Remember, X_C decreased as frequency was increased. Also remember that X_L increased as frequency increased. So, KEMET builds a device which has very little inductance and has a lot of capacitance, but if the frequency is raised to a high enough value, X_C is eventually overtaken by X_L and the capacitive device now acts like an inductor. If impedance is plotted with logarithmic scales, a graph that looks like the one on the next page is produced. Where the capacitive reactance is equal to the inductive reactance, the self-resonant point is produced. If there were no resistance in the circuit, the impedance would drop to zero at this point.



Practical capacitors frequently look more like this figure because they do include resistance. Exactly at the self-resonant point they act entirely like a resistor.



Pure resistance does not change with frequency. In practical capacitors, there isn't the simple series circuit, but rather a fairly complex mixture of resistance, capacitance and inductance. The result is, as measured at the terminals of the capacitor, that resistance declines with frequency. Because it really is not a pure resistance, it's called ESR or "Equivalent Series Resistance." KEMET catalogs include graphs of ESR for many styles of capacitors.

Inductance, which arises primarily from the fact that lead wires must be put on the capacitors, is seldom a problem at low frequencies, although as clock rates of computers increase, capacitors have been designed to minimize inductance. Resistance, however, is quite often a problem because it limits the power-handling capability of the capacitor. An ideal capacitor (or an ideal inductor) would produce no heat when current passes through it. The heat which is produced in practical devices comes from the resistance which cannot be eliminated completely. Because it has this importance, a measure of the resistance is frequently specified. ESR could be used directly, but it has been found much more convenient to use an expression called *dissipation factor*. "DF" is the ratio of resistance to capacitive reactance. The higher the resistance, the higher the DF and generally the capacitor is lower quality. Because in high quality capacitors the "DF" is rather small, it is frequently expressed in percent. It is better understood as 3% than 0.03.

$$DF = \frac{R}{X_C}$$

Dissipation Factor

By talking about DF rather than ESR, there is only one factor which represents a measure of capacitor quality applicable to a fairly wide range of capacitance values. With ESR, it would be necessary each time to specify the value of capacitance.

The expression for DF may also be written as below. This is simply the result of substituting the component factors X_C .

$$DF = 2\pi fCR$$

Capacitors in electronic circuits are normally not subjected to very large AC currents. Upon occasion the power-handling capability of electronic capacitors must be considered. It frequently comes up in filter design where the expression "AC ripple" is used. DC power supplies attempt to make pure direct current by filtering out fluctuations. These fluctuations are like ripples on the surface of a pond and represent AC passing through the capacitor. All would be well except that capacitors which have zero resistance cannot be built.

To calculate power, the equation below is used, which requires that the AC voltage across the capacitor be known as well as the AC current flowing through the capacitor. (There might be a DC voltage at the same time, but remember that there cannot be a steady DC current through a capacitor. If there is a pulsating DC, it must be treated like AC.) There is nothing wrong with this expression except its inconvenience. If a capacitor is working in a circuit, it would be relatively easy to measure the voltage across it, and not too difficult to measure the current through it, but designers would like to know ahead of time what is going to happen based upon ratings in KEMET catalogs. The first step towards simplification looks like things are more complicated, but that may not be the case.

$$P = EI$$

P = Power in watts
 E = Potential in volts
 I = Current in amperes

Power Equation

$$E = IR$$

E = Volts
 I = Amperes
 R = Ohms

Ohm's Law

Here is an indispensable aid to electronic engineers, Ohm's Law.

If in Ohm's Law, IR is substituted for E in the power equation, we get this result, which lets us calculate power if only the current and the resistance are known. The resistance which dissipates heat in capacitors is the ESR for which there are typical values, so now only the AC current, " I ," has to be found.

$$P = EI$$

$$= (IR) I$$

$$= I^2 R$$

$$E = IZ$$

$$\text{or } I = \frac{E}{Z}$$

Ohm's AC Law

Return to Ohm's Law, which was originally developed for DC circuits, and plagiarize slightly by substituting impedance, Z , for R . Alternating current, remember, is impeded in three ways, all of which are combined in the expression Z .

Now take the new expression for I , return to the power equation, and substitute E/Z for I . This one is easy to solve.

$$P = I^2 R$$

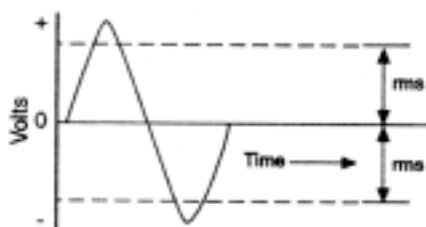
$$= \left(\frac{E}{Z}\right)^2 R$$

$$= \frac{E^2 R}{Z^2}$$

KEMET specifications are written to be most useful for designers. It is first established experimentally how much power each physical size of capacitor can handle without getting too hot. (If it gets too hot,

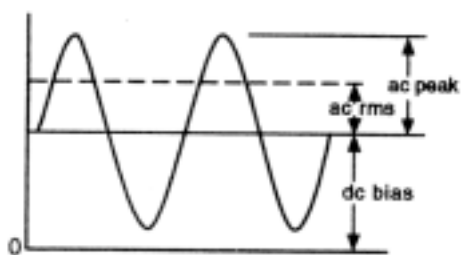
its failure rate goes up.) Then the catalog impedance curves are consulted to get the value of Z, the ESR curves to get the value of R, and the ripple voltage which would be allowed can be calculated.

This AC voltage is known as the “rms” voltage. Looking at the sine wave again, it can be seen that the average voltage will be zero. People can get killed with averages, so some smart fellow figured out the AC voltage which produces the same heating effect as direct current. It is called the “root mean square” or “rms” voltage. It is equal to the square root of two divided by two, or about 0.7, times the peak AC voltage. (Don’t forget the earlier caution on non-sine waves.)



Root Mean Square Voltage

The peak voltage is important for another reason. All capacitors have a rated voltage which should not be exceeded by anything – neither by DC nor the peak AC. So, the peak value must be calculated as a second restriction in AC applications. Film capacitors and ceramic capacitors are not polar devices. They will work equally well with either positive or negative polarity applied. Tantalum capacitors are not so flexible, and cannot be allowed much reverse voltage. If pure AC were applied, the voltage would be in reverse half the time. The answer to this dilemma is called bias voltage. Both AC and DC voltage are applied to prevent reversal. At the same time, we must not raise it too high or the rated voltage will be exceeded with the peak AC.



AC plus DC Bias

Now that we have reviewed the general characteristics of capacitors, let’s look at the applications of the two classes of KEMET capacitors.

$$P = \frac{E^2 R}{Z^2}$$

$$\text{or } E^2 = \frac{P Z^2}{R}$$

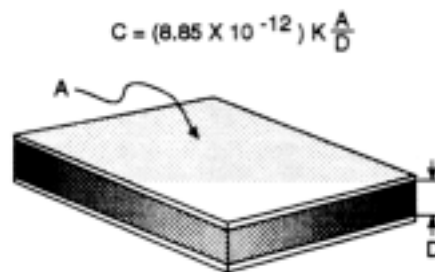
$$E = Z \sqrt{\frac{P}{R}}$$

Ripple Voltage

PART II

FUNDAMENTALS OF KEMET CAPACITORS

Before proceeding to KEMET capacitors, let’s take a minute to review some terms. Here once more is the capacitance equation, where A is the area of opposing electrodes, D is the separation between electrodes and K is the dielectric constant. The value of K depends on the specific dielectric material, and the higher K becomes, the more capacitance we would get if nothing else changes. The constant, 8.85×10^{-12} , was derived for units of D in meters, A in square meters, and C in farads (that is, one million microfarads).

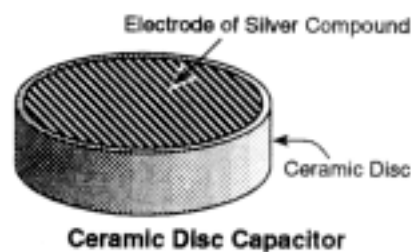


The Capacitor Equation

The practical designs of KEMET capacitor types all develop A and D. The value for K comes from selection of materials and not from any geometric arrangement of component parts.

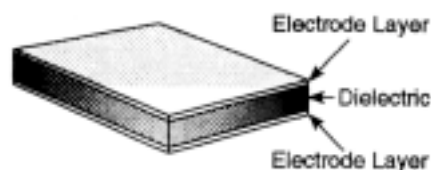
With the primer completed, we will now discuss ceramic capacitors.

There is one form of ceramic which looks almost exactly like the classical model of a parallel plate capacitor. A square or circular-shaped ceramic dielectric is prepared and coated with conductors on each flat face. If the value of K is known for the dielectric, the area of the conductors and the thickness of the dielectric can be measured, and the capacitance can be calculated directly.



Ceramic Disc Capacitor

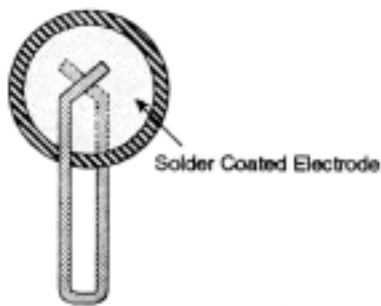
A circular shape is called a “ceramic disc” capacitor. If a square or rectangular shape is used, the industry calls it a “single plate” element.



Single - Plate Ceramic Element

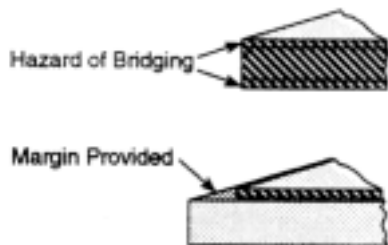
In commercial practice, the dielectric is made from finely powdered materials, the chief of which is barium titanate. Disc elements are pressed in dies and then fired at high temperature to produce a very dense structure. Single-plate elements are usually cut from larger sheets of fired ceramic material. Electrodes for both discs and single-plates are formed from a compound containing powdered silver, powdered glass, and an organic binder. This material is screen-printed onto the discs or sheets from which the single plates will be cut. Another firing step removes the binder and melts the glass, binding the silver glass matrix to the ceramic surfaces.

The outer surface is easily solderable, and wires are usually attached as seen here in a radial configuration. The hairpin-shaped wires are springy enough to hold the ceramic elements while the assembly is dipped in solder. The lower end of the hairpin is cut off later. This process can be mechanized readily, and dipped discs are among the cheapest capacitors available.



Disc Ceramic with Lead Wires

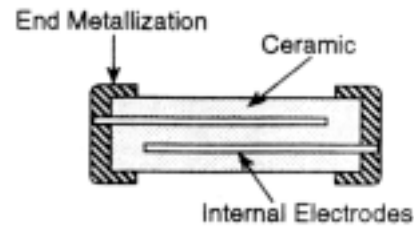
Unless some special means is taken to remove the electrode compound from the periphery of the single plate element, there is a hazard of conductors bridging across the dielectric to short-circuit the capacitor. Single plates could be printed like discs, but the feeding and locating problems increase cost and reduce accuracy of capacitance achieved.



Single Plate Shorting Hazard

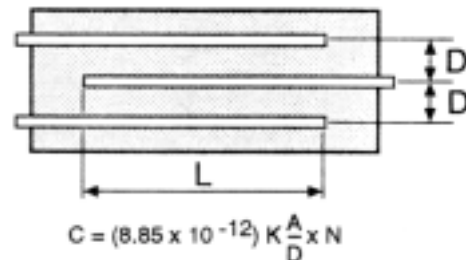
A much more sophisticated design is called the "monolithic" ceramic capacitor. It offers much higher capacitance per unit volume. It is seen here in a cross-sectional view and in simplified form. The ceramic material acts both as dielectric and as encapsulant of the basic element. Electrodes are buried within the ceramic and exit only on the ends. The ends are surrounded

with the same type of silver-glass compounds discussed earlier. Only two electrodes are seen here, but 20 or 30 electrodes are very common in commercial practice and 60 or 80 might be used to obtain larger values of capacitance.



Monolithic Ceramic Element

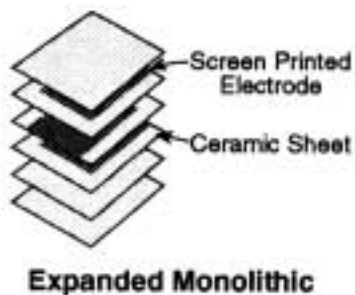
The diagram below shows three electrodes in use. The addition of the third electrode has double the value of capacitance because two layers of the dielectric are now in use. The old equation for capacitance may be modified by the addition of the term, N , to indicate the number of layers of dielectric in use. The thickness of the layer represents the plate separation, D , in the equation, while the area, A , is the area of dielectric which appears between opposing electrodes. The dimension, L , in the sketch is representative of this area; the remainder of the electrode length does not face electrodes of opposing polarity, and these portions of the electrodes act only as conductors to the outside world.



The manufacturing process for monolithic ceramics is much more complicated and sophisticated than that needed for discs or single plates. The powdered ceramic materials are mixed with a binder and cast on moving belts into thin flexible sheets which are wound onto reels and stored. The sheets are then printed with electrode patterns. The "ink" used in this printing is pigmented with finely-divided precious metals, usually chosen from among platinum, palladium and gold. Precious metals are necessary because the electrodes must pass through the firing kiln (above 1000°C) along with the ceramic, and oxidizing atmosphere must be maintained in the kiln to develop the desired ceramic properties. The precious metal electrodes represent a major cost element in making monolithic ceramic capacitors.

After the ink is dried, pieces of sheet are stacked above one another, each piece representing one dielectric layer. The electrode patterns are printed so that alternate electrodes exit from opposite ends. Finally, cover layers which do not bear electrodes are placed on top and bottom. The whole assembly is

compressed and then fired. During firing, the ceramic sinters together into one homogeneous structure from which we get the name “monolithic.” A much more complete description of the construction and the characteristics produced will be available in the program on ceramic capacitors.



Basic to the ceramic capacitor are the properties of the dielectric materials. There are many formulations in use to achieve the special characteristics of finished capacitors. In general, stability of capacitance with respect to temperature and voltage are sacrificed when large values of K are sought. While many special formulations are sold, the industry is concentrating on three general areas. We may call them stable, semi-stable, and general purpose. The COG (which is called NPO by almost everybody but specification writers) is highly stable with respect to temperature and also with respect to voltage and frequency. The others begin to develop wilder and wilder deviations in capacitance versus temperature as the value of K goes up. Nevertheless, they are very useful in applications where temperature changes little.

	Stable	Semi-stable	General Purpose
Symbols	COG or NPO	X7R	Z5U
K	60	1500	5000
Temperature Characteristics	0 ±30 ppm/°C	±15% ΔC -55 to 125°C	+22, -50% ΔC 10 to 85°C

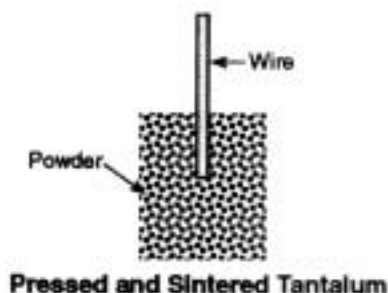
The volumetric efficiency of ceramics comes from the high values of K which are possible. This result is in contrast with tantalums and other electrolytics which gain efficiency primarily from very close spacing of electrodes. A 50-volt ceramic dielectric, for example, would be about 60 times as thick as a 50-volt tantalum oxide dielectric.

Now on to the next major class of electrodes. The solid tantalum capacitor is generally included in the class of “electrolytic” capacitors, although it doesn’t belong there. An electrolytic capacitor is one which uses an electrolyte for at least one of the electrodes. An electrolyte must generally be made of some chemically ionizable compound dissolved in a liquid. The solid tantalum capacitor (also sometimes called a dry tantalum capacitor) uses manganese dioxide, rather than a liquid electrolyte, as an electrode. Because of similar characteristics and historical development, the manganese dioxide came to be called a solid electrolyte, but it really is not; it falls generally into the class of semi-conducting solids.

The basis of the solid tantalum capacitor is tantalum. Tantalum is an element with certain properties that produce the characteristics found so desirable in finished capacitors. Foremost, of course, is the fact that it is a “valve” metal (aluminum is another) upon which one may grow very uniform and stable oxides with good dielectric properties. The dielectric constant of tantalum oxide (at 26) is relatively high. To form a high quality oxide film requires very high purity of the metal substrate. Tantalum melts at 3000°C and can be worked above 2000°C in vacuum. Under these conditions, most impurities can be evaporated and pumped away. Finally, tantalum is relatively easy to work mechanically. It can be ground to powder, rolled to sheet, drawn to wire, bent and formed without great difficulty at room temperature.

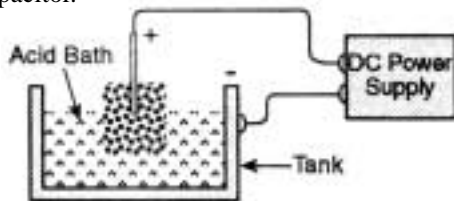
Characteristics of Tantalum
Valve metal
Excellent dielectric properties of oxide
Excellent purification process available (high vacuum at 2000°C)
Easily worked mechanically

To make capacitors from this material, tantalum powder and tantalum wire are needed. These two are pressed together, usually with some form of organic binder which is later removed. The pressed form is normally cylindrical for leaded capacitors and is usually rectangular for surface mount types. While it is also possible to press only the powder and weld on the wire later, the pressed in wire-and-powder assembly shown here is by far the most popular method. These pellets are sintered in vacuum furnaces. Sintering is a process of slow fusion between adjacent surfaces, so that when the pellets emerge from the furnace they are strong mechanically and have shrunk somewhat from their original size. About half the volume of the sintered powder remains as void space.



The pellets are then immersed in an acid bath and connected to the positive terminal of a DC power supply. The flow of current causes a layer of tantalum pentoxide, Ta_2O_5 , to grow on all exposed surfaces of the tantalum. The exposed surface includes the wire and both external and internal surfaces of the sintered powder. The internal surface is over 100 times the apparent external area. The oxide layer later will become the dielectric of the capacitor. One electrode of the parallel-plate model is

the tantalum metal; the second electrode will be applied in subsequent processing steps. The effective area of the capacitor becomes the entire surface of the tantalum pentoxide dielectric which can be contacted by the second separation between electrodes is the thickness of the oxide layer. This thickness is controlled by the voltage applied from the power supply. The higher the voltage, the thicker the oxide layer grows. Greater separation between electrodes means lower capacitance, of course, but it also means a higher voltage rating for the finished capacitor.

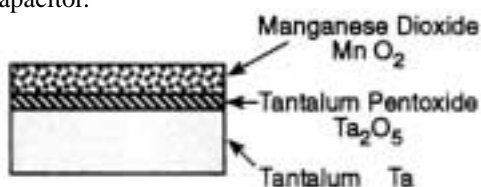


Anodizing

The second electrode is the semi-conducting manganese dioxide, MnO_2 . To apply this material, the porous pellet is dipped into a manganous nitrate solution which wets all surfaces and fills up the pores. When the pellets are later heated, the water from this solution is evaporated and then the nitrate decomposes to form the oxide according to this chemical equation. The MnO_2 layer covers nearly all the internal surfaces and extends part way up the wire.

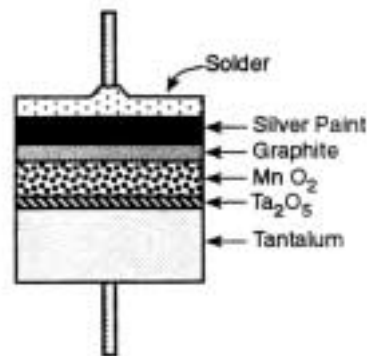


Look at one small portion of the pellet at this point, and see the tantalum substrate, the tantalum pentoxide grown upon the substrate, and, finally, the manganese dioxide deposited upon the tantalum pentoxide. It begins to look familiar as a parallel-plate capacitor.



Tantalum Pellet

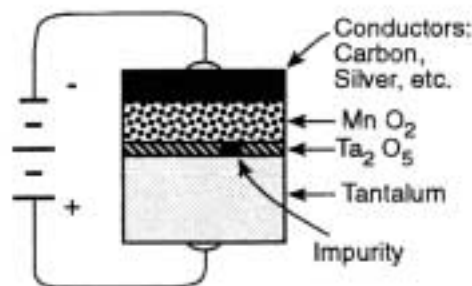
The rest of the processing is needed only to gain electronic contact to the electrodes. It is easy to weld an external lead wire to the stub of the tantalum wire, but contacting the MnO_2 is more difficult. To do this, the pellets are dipped into water containing a very finely divided carbon powder. After the water is evaporated, a layer of carbon (actually graphite) is left on all surfaces of the MnO_2 . Resistivity of the graphite is much lower than that of MnO_2 , and the fine particle size of the graphite enables this material to touch nearly all the very irregular MnO_2 surface. On top of the graphite, a silver-pigmented paint is applied. The silver is held by an organic resin and presents a solderable surface to facilitate attachment of the second lead wire. Putting all the layers together gives us a section which looks like this, with two wires being shown as indicative of external connection:



All Tantalum Layers

The encapsulation of a solid tantalum capacitor can follow several courses. The original design was soldered inside a metal can closed with a glass-to-metal hermetic seal. The next commercial design used potting with an epoxy resin inside of a pre-molded plastic shell. Later came transfer molding with epoxy, and then dipping in liquid epoxy resin. The final step in evolution is the tantalum chip, which has been encapsulated in epoxy and has several innovations in terminal design to provide protection against the rigors of directly soldering onto ceramic or glass epoxy substrates.

Much work has gone into statistical treatment of failure rates of solid tantalum capacitors because these capacitors possess a unique "healing" mechanism which results in a failure rate apparently decreasing forever. The MnO_2 provides the healing mechanism. If a fault, perhaps some impurity, produces an imperfection in the dielectric layer, a heavy current will flow through that minute area when a DC potential is applied to the capacitor. The current also flows through the MnO_2 immediately adjacent to the fault. Resistance of the MnO_2 to this current flow causes localized heating. As the temperature of MnO_2 rises, this material is converted to a lower oxide of manganese, perhaps Mn_2O_3 , with much higher resistivity. The increase in resistance decreases the current flow. If this mechanism is successful, the current flow is reduced before localized heating goes too far, preventing a short circuit. Without this mechanism, the solid tantalum capacitor would never have gotten off the ground commercially.



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